Deep-Seated Landslide Research Strategy

Upslope Processes Scientific Advisory Group

19 March 2018-CMER Review Draft

1 BACKGROUND

In response to the deep-seated Hazel landslide on Highway 530 and the North Fork Stillaguamish River (March 2014), the Washington Forest Practices Board (Board) requested the Timber/Fish/Wildlife Policy Committee (Policy):

- Review current Washington State forest practices rules for activities on deep-seated landslides in glacial deposits and their associated groundwater recharge areas; and
- Develop recommendations for future research including research on non-glacial deep-seated landslides, update guidance, and update rules if necessary.

Policy drafted and then received Board approval for an Unstable Slopes Proposal Initiation (PI) to address issues raised in written material and testimony at the 10 November 2015 Forest Practices Board meeting (Timber/Fish/Wildlife Policy Committee 2016). The PI included questions related to groundwater recharge in non-glacial deep-seated landslides, the potential for reactivation of dormant deep-seated landslides, and the run-out potential for deep-seated landslides.

Per Board request, Policy directed the Cooperative Monitoring, Evaluation and Research Committee (CMER) via the Upslope Processes Scientific Advisory Group (UPSAG) to develop a Deep-seated Landslide Research Strategy (hereafter Strategy). This Strategy includes descriptions of projects, identifies their respective priorities, timelines, and estimated costs; sequencing relative to each other; and describes the relationship between projects and their associated critical questions from the CMER Work Plan (2017-2019). The Strategy evaluates existing deep-seated landslide projects and revises, adds or replaces projects. We will evaluate the research limitations associated with each project during the study design phase.

The first step in developing the Strategy was to draft and execute a scope of work for a focused literature review and synthesis to update CMER on research assessing the effects of forest practices on groundwater recharge areas and deep-seated landslides in glacial materials (GDSLs). In response to the Board request, this literature synthesis and a second one focused on non-glacial (may include sediments and bedrock not associated with glacial materials) deep-seated landslides were completed (Miller 2016; 2017). Each synthesis provided recommendations for future research and tool development. We folded these recommendations into the existing Strategy outlined in the 2017-2019 Biennium CMER Work Plan. These will form the baseline for UPSAG to develop the Strategy further for inclusion in the 2019 CMER Work Plan. This Strategy developed by UPSAG/CMER will be brought to Policy and the Board for approval in 2018.

2 REGULATORY CONTEXT

The Forest Practices Habitat Conservation Plan (FP HCP) goal for the management of potentially unstable slopes is listed as a "Functional Objective" under "Sediment" in Schedule L-1 (Appendix N). This "Functional Objective" is defined as: Provide clean water and substrate and maintain channel forming processes by minimizing to the maximum extent practicable, the delivery of management induced coarse and fine sediment to streams (including timing and quantity) by protecting stream bank integrity, providing vegetative filtering, protecting unstable slopes, and preventing the routing of sediment to streams." More specifically, the timber harvest-related performance target measure for mass wasting sediment delivery to streams is to limit effects such that there is "no increase over natural background rates from harvest on a landscape scale on high risk sites" (Schedule L-1, Appendix N).

The intent of the FPHCP goal and its related forest practices rules is to avoid accelerating rates and magnitudes of mass wasting (landslides) that could deliver sediment or debris to a public resource (WAC 222-10-030 (4)) or that have the potential to threaten public safety (WAC 222-16-050 (1) (d)). The underlying assumption is that following the forest practices rules will achieve the performance goals, targets, and functional objectives of the FPHCP.

The forest practices rules protection strategy begins with definition of potentially unstable slopes or landforms with guidance from Board Manual Section 16 (WFPB 2015). Based on Board recommendation, in 2014 WADNR developed and implemented the Slope Stability Informational Form to be completed by applicants who propose a forest practices activity in or around rule-identified landforms (RIL) and included with their Forest Practices Application (FPA). This form is meant to provide additional information on the landslide screening tools used by applicants and includes potentially unstable slopes in or around proposed forest practice activities. Landowners may either avoid the area or conduct a risk evaluation through the State Environmental Policy Act (SEPA) process. The rule protection strategy relies on the ability of forest managers and regulators to recognize and mitigate for unstable slopes within the FPA and approval process.

3 Strategy Overview and Critical Questions

In Section 3, we briefly describe 12 projects, and the origin and current status of each. This information is then summarized in Table 1. Below Table 1, we describe how several of the uncompleted projects logically sequence from one to the next. And then we link the critical questions to the projects. In Section 4, each project is described in more detail. In Section 5, we explain how we envision implementing this strategy and provide a preliminary budget.

<u>Summary of Projects</u>

The 2017-2019 Biennium CMER Work Plan proposed several projects that address the effects of forest practices on deep-seated landslides. The critical questions focus on the reactivation of existing landslides, so the Strategy reflects those questions. While potentially unstable landforms may present indicators of future deep-seated failure (such as surface cracks), it is impossible to directly study future sites of activation because we cannot predict these occurrences. However, the efforts described below may identify geologic settings (e.g., lithology, geometry, stratigraphy) with elevated forest practices sensitivities leading to the possibility of identifying potential sites of new activation. One of these projects, the Model Evapotranspiration (ET) in Deep-Seated Landslide Recharge Areas Project (4.1; Sias 2003), has been completed. Its purpose was to modify a pre-existing ET model using data available at that time. Three other projects have undergone initial scoping, but remain on hold: the Evapotranspiration Model Refinement Project (4.11; Sias 2007), the Groundwater Recharge Modeling Project (4.8; Waldrick 2007), and the Landslide Classification Project (4.6; Gerstel 2007). The Evapotranspiration Model Refinement Project would be improved by future empirical research by better parameterization of critical model components identified as weaknesses by Sias (2003) in the original model. The Landslide Classification Project would categorize deep-seated landslides by attributes that might be differentially influenced by forest practices (i.e., we could reasonably argue that some stratigraphic columns might not be influenced by harvest-related decreases in ET while others might be strongly influenced). This project, as presented below, has been modified to include empirical evaluation of relationships of river undercutting, precipitation, and land use with activity level (e.g. relict, dormant or active) of deep-seated landslides in a category. The Groundwater Recharge Modeling Project was, and remains, a proposal to build groundwater recharge models for one to several deep-seated landslides (or conceptual versions). This effort will identify which categories of deep-seated landslides are potentially responsive to various strategies of timber harvest, and will tie changes in ET to groundwater responses in a landslide. Deep-seated landslide categories chosen for this modeling effort would be informed by the

Landslide Classification Project. Two literature reviews, one for glacial deep-seated landslides (Project 4.2; Miller 2016) and one for non-glacial deep-seated landslides (Project 4.3; Miller 2017), were completed, and the resulting recommendations were included in this Strategy. The Board Manual Revision Project (4.4) is acknowledged as an ongoing and iterative project whereby updates to Board Manual Section 16 will be recommended whenever implementation of the projects proposed in this Strategy produces results useful to the Board Manual.

The Deep-Seated Landslide Map Project (4.5) originates from the CMER Work Plan; it has never been scoped and its current vision, as described in more detail in Section 4, has been strongly influenced by recommendations in the two literature syntheses. This project has three phases:

- Objective 1 – to augment existing mapping from high quality data sets with additional field work to identify a sample of glacial deep-seated landslides for Project 4.6 – Landslide Classification;
- Objective 2 – to map and build attribute tables for representative valley-fill glacial deep-seated landslides and for known spatial concentrations of non-glacial/bedrock deep-seated landslides, both to identify samples for Project 4.6; and
- Objective 3 – to complete mapping of valley-fill glacial deep-seated landslides where other high quality mapping does not exist in order to have complete mapping of these features.

The GIS-Based Landslide Stability and Sensitivity Toolkit (4.7) is identified as a separate project to clearly capture its primary objective – to create user-friendly GIS tools to help a practitioner screen, characterize and assess deep-seated landslides remotely. In reality, these tools will be built as Projects 4.5, 4.6, 4.8 and 4.9 are accomplished. This project was recommended in the literature syntheses (Miller 2016).

The Physical Modeling Project (4.9) was recommended in the literature syntheses and not currently in the CMER Work Plan or previously scoped. The project will provide slope stability modeling of individual deep-seated landslides (or conceptual versions) that are potentially responsive to forest practices. It will tie groundwater modeling from Project 4.8 to slope stability modeling to assess how changes in groundwater recharge may affect the stability of the landslide. As with Project 4.8, the physical modeling will also be used to refine the landslide classification project to better identify landslide settings that are sensitive to forest practices.

The Landslide Monitoring Project (4.10), which was recommended in the literature syntheses and not currently in the CMER Work Plan or previously scoped, will be long-term monitoring of one or more select sites. It will provide data to validate modeling, and directly measure landslide response to timber harvest. This project will also contribute to and inform the analysis techniques developed during the groundwater and physical modeling projects.

The Empirical Evaluation of Deep-Seated Landslide Density, Frequency and Runout by Landform Project (4.12) originates from the Unstable Slopes Criteria Project Research Alternatives document; it is not currently in the CMER Work Plan or previously scoped, and the Unstable Slope Criteria TWIG is not planning to work on it. As proposed here in the Strategy, it will not be an individual project but research ideas within it are included in other projects.

Table 1: Summary of Project Origins and Status

Project Title	**Project Origin**	**Status**
4.1 Model Evapotranspiration in Deep-Seated Landslide Recharge Areas	CMER Work Plan	Completed
4.2 Literature Synthesis of the Effects of Forest Practices on Glacial Deep-Seated Landslides and Groundwater Recharge	CMER Work Plan	Completed
4.3 Literature Synthesis of the Effects of Forest Practices on Non-Glacial Deep-Seated Landslides and Groundwater Recharge	Deep-Seated Landslide Proposal Initiation (PI)	Completed
4.4 Board Manual Revision	CMER Work Plan	On-going
4.5 Deep-Seated Landslide Mapping	CMER Work Plan	On-hold
4.6 Landslide Classification	CMER Work Plan/ Revised by PI	Scoped in 2007; On-hold
4.7 GIS-Based Landslide Stability and Sensitivity Toolkit	Recommendation from 4.2	Not previously scoped

4.8 Groundwater Recharge Modeling	CMER Work Plan	Scoped in 2007; On-hold
4.9 Physical Modeling of Deep-Seated Landslides	Recommendation from 4.3	Not previously scoped
4.10 Landslide Monitoring	Recommendation from 4.2	Not previously scoped
4.11 Evapotranspiration Model Refinement	CMER Work Plan	Scoped in 2007; On-hold
4.12 Empirical Evaluation of Deep-Seated Landslide Density, Frequency, and Runout by Landform	Unstable Slope Criteria TWIG	N/A

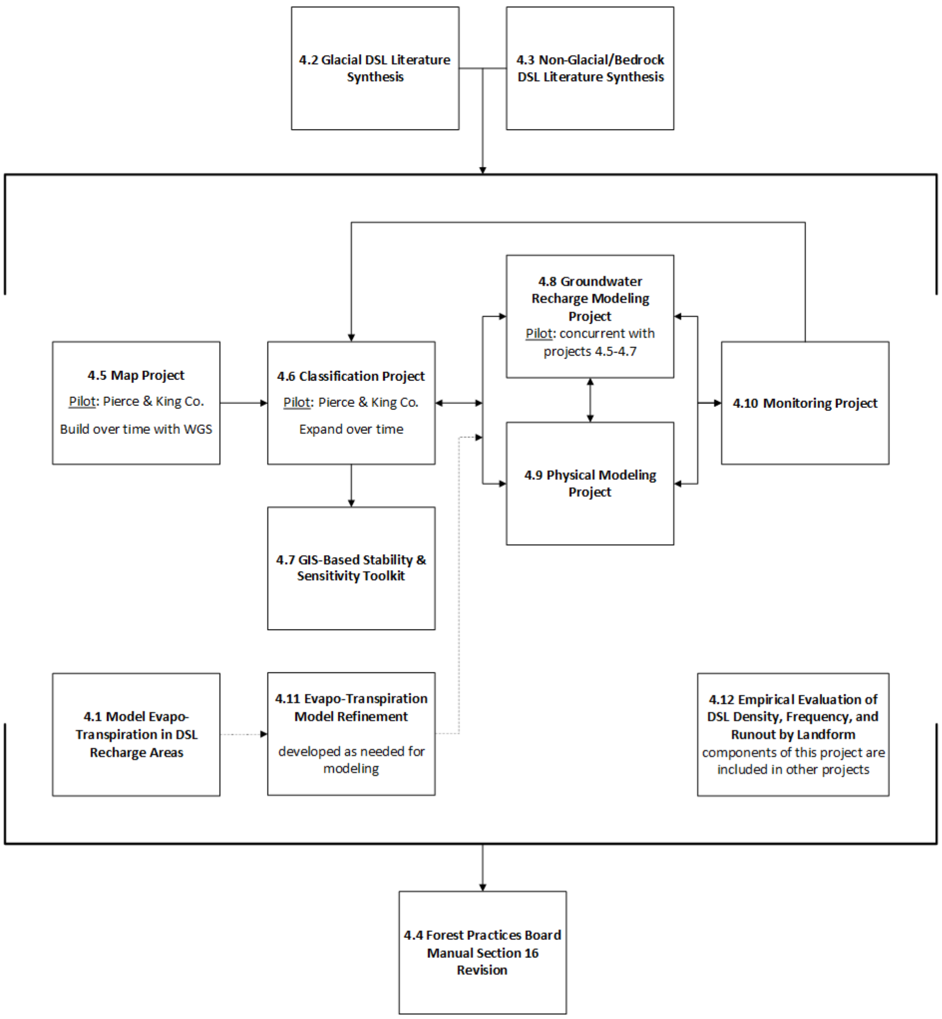
Sequencing of Future Projects

Project 4.4 Board Manual Revision is an on-going project that will be recommended by UPSAG whenever new information useful for Section 16 is produced by the other projects. Currently, UPSAG is evaluating whether the literature syntheses contain such information.

The Strategy is comprised of a series of linked projects (depending on funding), many of which inform subsequent project designs (Figure 1). Project 4.5 Deep-Seated Landslide Mapping is critical to the success of Project 4.6 Landslide Classification because (1) appropriate populations of glacial and non-glacial deep-seated landslides must be identified before they can be empirically evaluated for responses to natural processes and land use and (2) before they can be classified in a manner meaningful to our initial understanding of the potential for responses from changes in groundwater recharge. Also, complete mapping of glacial valley-fill deep-seated landslides is an important rule tool. Then Project 4.8 Groundwater Recharge Modeling will be done for one to several of the categories identified by Project 4.6. This will, in an iterative manner, refine the categories. Project 4.9 Physical Modeling of Deep-Seated Landslides will be done for one to several of those refined categories. Finally, Project 4.10 Landslide Monitoring will instrument representative deep-seated landslides from categories that appear, from the modeling efforts of Projects 4.8 and 4.9, to most likely to respond to forest practices.

Several other projects are included in the Strategy that are not directly linked in the research pathway described above. Project 4.7 GIS-Based Landslide Stability and Sensitivity Toolkit is a result of Projects 4.5, 4.8 and 4.9 and is only identified as a separate project to emphasize the need for user-friendly GIS tools. Project 4.11 Evapotranspiration Model Refinement is only necessary if we find that Projects 4.8 and 4.9 need a better model for estimating ET than Sias (2003) or another, more current, model. Project 4.12 Empirical Evaluation of Deep-Seated Landslide Density, Frequency, and Runout by Landform will not be done as an individual project, because parts of it will be incorporated into Projects 4.5 and 4.9 with particular emphases placed on empirical linkages between natural factors and land use to deep-seated landslide activity and on run-out estimates.

Figure 1: Conceptual linkage of the projects presented in the deep-seated landslide strategy.



<u>Linkages to Critical Questions</u>

The Strategy will seek to address Critical Questions from:

1) The Unstable Slopes Rule Group Glacial Deep-Seated Landslide Program and Mass Wasting Effectiveness Program (Cooperative Monitoring, Evaluation and Research Committee 2017); and

2) Additional questions about the effects of forest practices on non-glacial deep-seated landslide processes posed by the Timber/Fish/Wildlife Policy Committee in the 2016 Proposal Initiation (Timber/Fish/Wildlife Policy Committee 2016).

Since many of these questions are broad, we expect that projects will be addressing different aspects of the questions and we will identify more specific research questions for each project during the scoping and study design process. The Critical Questions are identified below and the relevant project information for each question is listed. Project details can be found in Section 4 of the Strategy.

GLACIAL DEEP-SEATED LANDSLIDE PROGRAM:

- *Does harvesting of the recharge area of a glacial deep-seated landslide promote its instability?*
    - Evapotranspiration Modeling (Project 4.1): Assessed changes in ET with timber harvest and found that significant hydrologic effects could result and these effects are likely to be unfavorable for slope stability, but these modeling results were not directly tied to slope stability modeling.
    - Literature Review of Forest Practices Effects on Glacial Deep-Seated Landslides (Project 4.2): Literature review found few sources that directly addressed this question, but identified the conceptual model linking harvest of the recharge area with increases in groundwater infiltration and changes in slope stability.
    - Deep-Seated Landslide Mapping (Project 4.5): Landslide mapping will identify deep-seated landslides in glacial materials, map their recharge area, and characterize their subsurface geology based on existing mapping and field evidence. The project will describe the harvest history and associate other important attributes of the site, identified in the literature review, with the observed activity level of the landslide.
    - Landslide Classification (Project 4.6): Landslide classification will identify if there are groups of landslides that appear to be more responsive or have a higher potential to respond to harvest within the groundwater recharge area. The classification will be revised based on groundwater and physical modeling results

from other projects to focus on the groups of landslides that appear to be the most responsive to forest practices.

- Groundwater Modeling (Project 4.8): Groundwater modeling of landslides that are potentially responsive to timber harvest is proposed to define the groundwater recharge area and tie changes in ET to groundwater response in the landslide. The modeling in the pilot will also be used to refine the identification of landslide settings that appear sensitive to forest practices.
- Physical Modeling (Project 4.9): Physical modeling of landslides that are potentially responsive to forest practices will tie groundwater modeling from Project 4.8 to slope stability modeling to assess how changes in groundwater recharge may affect the stability of the landslide. The physical modeling will also be used to refine the landslide classification project to better identify landslide settings that may be sensitive to forest practices.
- Landslide Monitoring (Project 4.10): Long-term monitoring of the select sites will provide data to validate modeling and directly measure landslide response to different timber harvest strategies.
- ET Model Refinement (Project 4.11): If changes in groundwater recharge on the general scale expected from timber harvest promotes landslide instability, then selecting or refining an appropriate ET model will be critical for tying forest practices to groundwater infiltration. This can be used to evaluate the effect of different harvest techniques, such as thinning, on groundwater recharge.

- *Can relative levels of response to forest practices be predicted by key characteristics of glacial deep-seated landslides and/or their groundwater recharge areas?*
  - Literature Review of Forest Practices Effects on Glacial Deep-Seated Landslides (Project 4.2): Literature review found few sources that directly addressed this question, but identified the conceptual model linking harvest of the recharge area with increases in groundwater infiltration and changes in slope stability. Because of the variable geotechnical and hydrogeologic properties of glacial materials, Miller (2016) suggested that deep-seated landslides can be classified into groups that respond differently to changes in groundwater recharge.
  - Landslide Classification (Project 4.6): Landslide classification will identify if there are groups of landslides that appear to be more responsive or have a higher potential to respond to harvest within the groundwater recharge area. The classification will be revised based on groundwater and physical modeling results

from other projects to focus on the groups of landslides that appear to be the most responsive to forest practices.

- GIS Toolkit (Project 4.7): Tools developed as a part of the landslide classification project could be used to statistically evaluate different landslide attributes measured during the mapping project and their association with activity level.
- Groundwater Modeling (Project 4.8): Groundwater modeling of landslides that are potentially responsive to timber harvest is proposed to define the groundwater recharge area and tie changes in ET to groundwater response in the landslide. The modeling in the pilot will also be used to refine the identification of landslide settings that appear sensitive to forest practices.
- Physical Modeling (Project 4.9): Physical modeling of landslides that are potentially responsive to forest practices will tie groundwater modeling from Project 4.8 to slope stability modeling to assess how changes in groundwater recharge may affect the stability of the landslide. The physical modeling will also be used to refine the landslide classification project to better identify landslide settings that are sensitive to forest practices.

MASS WASTING EFFECTIVENESS MONITORING PROGRAM:

- *Are unstable landforms being correctly and uniformly identified and evaluated for potential hazard?*
  - Literature Review of Forest Practices Effects on Non-glacial Deep-Seated Landslides (Project 4.3): Miller (2017) suggested that evaluation methods for forest practices effects on deep-seated landslides are inconsistent.
  - Deep-Seated Landslide Mapping (Project 4.5): Mapping will provide improved deep-seated landslide maps for forestlands.
  - Landslide Classification (Project 4.6): Landslide classification will identify if there are groups of landslides that appear to be more responsive or have a higher potential to respond to harvest within the groundwater recharge area. These potential hazard classes will help direct the evaluation of the landslides.

DEEP-SEATED LANDSLIDE PROPOSAL INITIATION:

- Groundwater recharge areas (GWRA) of non-glacial (bedrock) deep-seated landslides:
    - *Are GWRAs associated with bedrock deep-seated landslides?*
        - Literature Review of Forest Practices Effects on Non-glacial Deep-Seated Landslides (Project 4.3): Miller (2017) found that groundwater recharge areas are associated with non-glacial deep-seated landslides.
    - *How do GWRAs affect bedrock deep-seated landslides?*
        - Literature Review of Forest Practices Effects on Non-glacial Deep-Seated Landslides (Project 4.3): Miller (2017) found that increases in pore pressure from increased groundwater recharge can initiate or accelerate landslide movement.
        - Groundwater Modeling (Project 4.8): Groundwater modeling of deep-seated landslides will help better define the extent of the groundwater recharge area for non-glacial landslides and characterize the subsurface flow paths associated with the landslide.
        - Physical Modeling (Project 4.9): Modeling will be used to assess the connection of groundwater recharge to slope stability in non-glacial deep-seated landslides.
    - *How do forest practices affect these GWRAs?*
        - Non-glacial deep-seated landslides will be included in the population of deep-seated landslides assessed and monitored in projects 4.5, 4.6, 4.8, 4.9, 4.10 and 4.11. These projects address this question as described for glacial deep-seated landslides.

- Reactivation potential of deep-seated landslides:
    - *What are the best methods to assess reactivation potential from dormant DSLs of any type?*
        - Literature Review of Forest Practices Effects on Non-glacial Deep-Seated Landslides (Project 4.3): Miller (2017) suggested that a combination of statistical analyses, geotechnical modeling, and landslide dating can provide insight into reactivation potential.
        - GIS Toolkit (Project 4.7): Tools developed as a part of the landslide classification project could be used to statistically evaluate different landslide attributes measured during the mapping project and their association with activity level.

        - Physical Modeling (Project 4.9): Slope stability modeling will be used to directly assess reactivation potential for landslides that appear to have a high sensitivity to forest practices.
        - Landslide Monitoring (Project 4.10): Miller (2017) suggested including radiocarbon dating of landslides in the monitoring project to develop an age distribution of landslides to assess frequency and changes in activity level through time.

- Complex/composite deep-seated landslide behavior:
    - *What are the characteristics of large landslides that may predispose them to long, rapid run-out or composite failure?*
        - Deep-Seated Landslide Mapping (Project 4.5): Mapping will provide the extent of the landslide run-out that is preserved in the existing topography. The project will identify associations between run-out distance and measured characteristics of the landslide. The activity state and style of landslide activity are characteristics that will be included in the landslide attributes.
        - Physical Modeling (Project 4.9): Modeling will be used to assess potential for run-out for selected classes of landslides identified in the Landslide Classification Project.

    - *What methods might improve prediction?*
        - Literature Review of Forest Practices Effects on Non-glacial Deep-Seated Landslides (Project 4.3): Miller (2017) found that several landslide attributes (topographic relief, landslide volume, and nature of the depositional zone) are associated with increased landslide run-out distance. Local calibrations of height to run-out relationships could be used to predict potential run-out length.
        - Deep-Seated Landslide Mapping (Project 4.5): Mapping will provide the extent of the landslide run-out that is preserved in the existing topography and measurements of the landslide height.
        - GIS Toolkit (Project 4.7): Tools developed as a part of the landslide classification project may be used to evaluate the relevant landslide attributes measured during the mapping project and relate these to the expected run-out distance.

        - Modeling results from the Groundwater Modeling (Project 4.8) and the Physical Modeling (Project 4.9) may identify more effective analysis methods and lead to improved prediction tools for composite/ complex landslide settings.

- Deep-Seated Landslide Run-out:
    - *What are the best tools to assess run-out potential for deep-seated landslides?*
        - Deep-Seated Landslide Mapping (Project 4.5): Mapping of landslide scar and deposit geometries from high-resolution digital elevation models and field surveys could be used to calibrate empirical models for representative rock types and glacial deposits across Washington. Resulting statistical models can be translated to maps of probability of runout extent.
        - Physical Modeling (Project 4.9): Physical run-out models may also be applied to deep-seated landslides.

4 Research Projects

Each of the projects identified below includes a status and a brief description of the project, followed by a Strategy recommendation. These recommendations are currently preliminary in nature and the questions may be further refined once a project is prioritized and funded by Policy and the Board. Once funding has been approved, UPSAG will provide greater detail on project specifics during the scoping/BAS (best available science) and study design phases of each new project (See CMER Protocols and Standards Manual, chapter 7, 2017). For completed projects, the description summarizes the results and limitations. Previously scoped projects have a summary of the existing scoping document and include any proposed revisions to the previous scope. New projects are also described and their potential alternatives identified. In an appendix, there are brief summaries from the current 2017-2019 Biennium CMER Work Plan or material appropriate for inclusion in a future CMER Work Plan (e.g., the 2019-2021 update).

4.1 Model Evapotranspiration in Deep-Seated Landslide Recharge Areas Project – Completed

This completed project developed and revised analytical models into a single product called GAET (Groundwater and Actual Evapotranspiration) for assessing the evapotranspiration (ET) and groundwater changes resulting from timber harvest (Sias 2003). This project sought to inform the question: *Does harvesting the recharge area of a glacial deep-seated landslide promote its instability?* The hypothesized linkage between changes in evapotranspiration and stability of deep-seated landslides is that timber harvest may lead to a decrease in evapotranspiration and this, in turn, could increase the amount of water entering the subsoil and the groundwater aquifer. The resulting higher pore pressure could increase landform instability. The project objectives were to assess the change in ET that may result from timber harvest, the groundwater storage response to predicted ET changes using the Penman-Monteith equation for estimating actual evaporation and transpiration rates, the Rutter interception model for estimating canopy wetness status, and the Dupuit-Boussinesq horizontal aquifer model for estimating groundwater storage. The project also assessed the potential for the GAET model to become a tool to assess stability of deep-seated landslides on managed forest lands having a rain-dominated winter and droughty summer climate.

The major conclusions of the project were that:

1) Winter evapotranspiration is a potentially non-negligible component of the annual water balance of an evergreen needle-leaf forest and may be significant also for non-forest (shrub) vegetation; and

2) Significant hydrologic effects could result from forest-to-shrub conversion and these effects are likely to be unfavorable for slope stability (Sias 2003).

We identified several limitations to the project and suggested recommendations for future research. Remaining uncertainty is largely tied to model selection and parameterization, and the author recommended making empirical determinations of the degree to which:

1) Cumulative winter ET over forest is non-negligible;

2) Vegetation conversion results in a significant decrease in cumulative winter ET; and,

3) The timing of the start of recharge season is changed after harvest.

Further, the aquifer parameter for different types of glacial-lacustrine deposits must be determined for use in the hydrogeological portion of the model. The author recommended that future research should determine the harvest-groundwater storage effect in glacial sediments.

We regard this project as complete, though limitations of the modeling hampered our ability to draw specific conclusions about groundwater recharge and slope stability. Moreover, the model is not recommended for use as a screening tool for evaluating groundwater recharge until after empirical studies to substantiate the hypothetical linkage between forest practices and wet season groundwater storage are conducted.

Strategy Recommendation

The GAET modeling project clarified that considerable uncertainty existed about model parameterization. These uncertainties have not been fully resolved. As recommended, developing the scope for an empirical study to look at cumulative winter evapotranspiration and the timing of the onset of groundwater recharge would provide data to help validate the GAET model; we propose such a study below (see Project 4.11). It also remains clear that an ET model will be a necessary component of both groundwater and physical modeling efforts (see Projects 4.8 and 4.9 below). However, the author recommended that characterization of the groundwater system should be the primary area of focus for research. Specifically, the current model suggests that decreases in evapotranspiration from clear-cut harvest of mature timber can increase the annual water available to the groundwater system, but understanding how "available water" actually influences groundwater hydrology in different settings and materials is so poor that refinements in GAET modeling would be uninterpretable even if such understanding were available. One approach to addressing this recommendation would be to measure the shallow groundwater response to different harvest treatments directly in different glacial materials; we also propose this study as a component of Project 4.8.

4.2 Literature Synthesis of the Effects of Forest Practices on Glacial Deep-Seated Landslides and Groundwater Recharge – Completed

We undertook the glacial deep-seated landslide literature synthesis in 2015 to provide updated background information to further help address the question: *Does harvesting of the groundwater recharge area of a glacial deep-seated landslide promote its instability*? While focused on deep-seated landslides in glacial deposits, the literature review also provided information relative to critical questions related to groundwater recharge, landslide behavior, and run-out posed in the 2016 Unstable Slopes Proposal Initiation Memo. The synthesis revealed that the sensitivity of glacial deep-seated landslides to forest practices is not only poorly understood, but that many of the effects of forest practices must be inferred using measurements for different land-cover types (Miller 2016). The literature review includes an annotated database, a GIS map product, and a synthesis report.

Miller (2016) found that the processes affecting soil water balance and groundwater recharge are well described, but few studies directly examine the effects of forest practices on water budget components. Also, geotechnical properties of glacial deposits are well characterized, and the location and saturation potential of these deposits largely govern the occurrences and activation of glacial deep-seated landslides. Increasing pore pressures, which can vary spatially and by depth due to the variable material properties of glacial deposits and fractures from internal displacement, commonly initiate landslide motion. These effects can allow these failures to persist over hundreds to thousands of years, with periodic movements. They can also, under certain poorly understood conditions, fail catastrophically, creating a rapidly moving deposit that can flow a considerable distance. Based on a review of geotechnical reports and letters, Miller (2016) concluded that the current standard of geotechnical practice as applied in the forest-practices arena did not include consistent methods for objective determination of sensitivity of glacial deep-seated landslides to forest practices, or for assessing hazards these landslides posed.

Strategy Recommendation

The literature review recommended several directions for continued research and tool development. These recommendations have been included in this Strategy in the form of new projects, or as a revision to projects previously scoped in the CMER Work Plan (see Tables 1 and 3).

4.3 Literature Synthesis of the Effects of Forest Practices on Non-Glacial Deep-Seated Landslides and Groundwater Recharge – Completed

This project resulted from the Board-approved Unstable Slopes Proposal Initiation to address issues raised in written material and testimony at the 10 November 2015 Forest Practices Board meeting. The literature review sought publications regarding forest practices effects on groundwater recharge areas for non-glacial deep-seated landslides, the reactivation potential of dormant landslides, and the behavior of complex/composite landslides with catastrophic failure and run-out potential. This literature review builds on the annotated database and landslide inventory created for the glacial deep-seated literature review and includes a separate synthesis report to address additional questions about slope stability in non-glacial materials. This review also helped address the question: *Does harvesting of the groundwater recharge area of a glacial deep-seated landslide promote its instability*?

Strategy Recommendation

The literature review recommended several directions for continued research and tool development. These recommendations have been included in this Strategy in the form of new projects, or as a revision to projects previously scoped in the CMER Work Plan (see Tables 1 and 3).

4.4 Board Manual Revision Project - Ongoing

This project is ongoing and iterative in nature. As new information or tools are developed that inform us about the potential influences of forest practices on different types and activity levels of deep-seated landslides, these should be added to the Board Manual (Section 16). In 2014, WADNR convened an "Expert Panel" to revise portions of the Board Manual related to deep-seated landslides and groundwater recharge. A TFW stakeholder group of qualified experts subsequently revised a section on landslide runout and potential delivery. The Board adopted the revised version of Board Manual Section 16 in March 2015, and the section on runout and delivery in November 2015. The 2014-2015 revisions to Section 16 provided new guidance regarding the amount of study needed to address different situations. The literature syntheses (Miller 2016 and 2017) may contain information appropriate for the Board Manual. Ultimately, each future project in this Strategy may improve Section 16.

Strategy Recommendation

Our plan is to update Board Manual 16 with relevant concepts, citations and tools as these are revealed by our efforts and/or by outside scientific research on deep-seated landslides. We are currently evaluating whether the 2016 and 2017 deep-seated landslide literature syntheses provided concepts and citations appropriate and necessary for inclusion.

4.5 Deep-Seated Landslide Map Project – Pre-Scoping

This project would build on the Washington Geologic Survey (WGS) ongoing efforts by providing a spatial inventory of deep-seated landslides where WGS does not focus its work, and increasing field work to acquire detailed attributes for variety of geologic materials and environmental settings. This mapping effort is critical for establishing the population of landslide types, processes, and spatial extents. It will be the foundation for most of the subsequent projects. Mapping inventory methods would be consistent with those used by WGS (Slaughter et al. 2017). WGS used the SLIP (Streamlined Landslide Inventory Protocol) approach to map the boundaries of landslide deposits in Pierce County from LiDAR-based digital elevation models (Mickelson et al. 2017) and we expect that similar methods will be used for the less populated forestlands around the state. This will require the continued acquisition of LiDAR for these areas. The WGS is expected to continue mapping deep-seated landslides as LiDAR data becomes available for successive counties, and UPSAG would coordinate mapping with WGS staff to augment their efforts with the information we need to implement this Strategy.

This project is both a rule tool that will help build a better landslide inventory for use by land managers and a sample that will provide the basis for selecting landslides and collecting an array of relevant field and remotely sensed data for the Landslide Classification Project. The SLIP-mapped landslide polygons that are included in the WGS product lack detailed attributes; they only indicate the level of confidence with the mapped boundaries. We would add field observations to determine landslide type, activity level, and verify or revise stratigraphic relationships. An exploratory approach will be used to interpret the field data and site history to develop hypotheses related to the influence of forest practices on deep-seated landslide activity. Ultimately, the linkages between landslide activity and influences including land-use and natural associations (e.g., river erosion, rainfall history), will be compiled from the analysis of historical aerial photography and specific field observations (e.g., tree curvature). Existing geotechnical and monitoring data available from state, county, and city agencies could also be used to help describe the mapped landslide polygons.

Strategy Recommendation

This will be the first project initiated under this Strategy to provide a selection of deep-seated landslides with relevant attributes for the Landslide Classification Project (Project 4.6). The goal would be to start with the published SLIP mapping and then attribute the landslide polygons with additional information that is relative to forest practices. The longer-term goal is to build a definitive landslide inventory for forestlands on valley-fill glacial deposits to provide a Rule Tool for evaluating groundwater recharge areas for glacial deep-seated landslides.

- Objective 1: Identify a sample of glacial deep-seated landslides from data sets such as the WGS mapping in Pierce and King counties so that a pilot of the Landslide Classification Project can be conducted.
- Objective 2: Building on WGS efforts, map and build attribute table for representative glacial deep-seated landslides (probably some in each major valley) and for known spatial concentrations of non-glacial/bedrock deep-seated landslide.
- Objective 3: Complete mapping not done by WGS for all valley-fill glacial deep-seated landslides in Washington (not all deep-seated landslides will be mapped as the necessary LiDAR data and effort are beyond our budget).

4.6 Landslide Classification Project- To Be Scoped

The purpose of the “Geo/Hydro/Geomorphic Landslide Classification Project,” as scoped in 2007 (Gerstel, 2007), was to develop GIS and field-based categories for deep-seated landslides in glacial deposits, known as ‘glacial deep-seated landslides’ (GDSL), which are based on geology (stratigraphy), hydrology, geomorphology, and topographic setting. We would then assess which categories may be more or less sensitive to changes in groundwater produced by upslope timber harvest (i.e., modeling efforts – see Project 4.8) and would ultimately guide where empirical studies would be conducted (see Project 4.9).

This project will use areas mapped in the Deep-Seated Landslide Map Project (4.5). The goal of the Classification Project would be to identify characteristics of deep-seated landslides such as landslide type, stratigraphy, size of the landslide and size of its groundwater recharge area, history of forest practices, or proximity to a river channel that could be used to separate landslides into different classes. These characteristics would be measured with a set of qualitative and quantitative metrics to be refined as a part of a pilot of Landslide Classification Project. In cases where existing geotechnical evaluation is available for the site, this would be incorporated into the analysis to determine if a forest practices correlation exists.

Co-incident with field mapping and aerial photo interpretation, spatial analysis using GIS-based tools would be used to extract topographic, land use and hydrologic attributes for the landslides from high-resolution digital elevation models and other spatial datasets. These attributes, which would be defined during the study design phase, could include the size, surface roughness, surface morphology and displacement of the slide, as well as the contributing surface area and hydrology; and could help define the classes of deep-seated landslides. Attributes could also form the basis for assessing the stability of the landslide by comparing them to activity level. While initially focused on landslides in glacial materials, the classification would be expanded to include non-glacial deep-seated landslides as the mapping becomes available.

The project would begin with a pilot study in glacial materials where landslide mapping exists, consistent with the scope of Objective 1 for Project 4.4. As of November 2017, this mapping has been completed for several areas in the state, including Pierce County and parts of King County. However, we will need to conduct additional mapping and attribute data collection to provide the data required for this project. Starting with a smaller geographic area as a pilot would allow the classification project to begin, while landslide mapping continues elsewhere. The pilot would seek to identify the relevant landslide classes that are present in the pilot area, based on an initial set of qualitative and quantitative criteria. Spatial analysis and statistical modeling, such as logistic regression analysis, would then relate the characteristics of the landslide to field-interpreted activity levels.

STRATEGY RECOMMENDATION

Create a classification of characteristic geomorphic settings and morphological types for glacial and bedrock deep-seated landslides. The project will begin with a pilot landslide population selected from mapping in King and Pierce counties (as well as other sources), that will develop an initial classification scheme while the deep-seated landslide mapping continues in other areas of glacial deposits. Once the initial categories of landslides have been identified, field assessment, and spatial and GIS analyses would be used to refine the categories. The GIS-based tools used to evaluate the categories would then be evaluated for inclusion in the Landslide Stability and Sensitivity Toolkit (Project 4.7). Following the pilot, the classification project will be expanded and refined as additional populations of landslides are mapped in Objective 2 of Project 4.5.

4.7 GIS-BASED LANDSLIDE STABILITY AND SENSITIVITY TOOLKIT - PRE-SCOPING

Miller (2016) suggested developing a series of GIS-based tools for assessing the stability and sensitivity to forest practices of deep-seated landslides. These tools would be developed as a part of the Landslide Classification Project (Project 4.6) to help define bins for further analysis. The tools will characterize the landslide geometry, hydrologic inputs and land use for individual landslides. As tools are identified and developed, they will be compared to field-verified activity levels and statistical analyses will be used to assess the relationship between these factors.

In the future, the toolkit could also use groundwater recharge information and slope stability modeling to estimate a Factor of Safety for each slide, if one can validate these models for populations of landslides. With the use of these models, evaluation of changes in groundwater recharge or changes in slope geometry could be used to assess landslide sensitivity. The tools might also be used for run-out prediction for a hypothetical failure at a specific landslide location.

The products of this project could include a map of the stability assessment results to use as a forest practice screening tool, a GIS-based toolkit for use in developing and reviewing geotechnical reports, and statistical relationships between landslide characteristics and slope stability that can be periodically refined as more landslides are assessed with the tools. Maps can also be produced to show the data elements used for the calculated rankings. These may include mapped landslide boundaries, landslide surface roughness, and delineation of the estimated contributing area, upslope geological and topographic features, proximity to streams, and other attributes that should be field-verified.

STRATEGY RECOMMENDATION

This project will be initiated as a part of the pilot for the Landslide Classification Project (4.6). Similar to the mapping project, the toolkit analysis will focus first on glacial deposits and then expand to a selection of bedrock deep-seated environments. Implementing the toolkit development as a part of the Landslide Classification Project will allow for the on-the-ground evaluations of the sites.

4.8 GROUNDWATER RECHARGE MODELING PROJECT – TO BE SCOPED

This groundwater recharge assessment is to be conducted on the generalized categories from the Landslide Classification Project. It will also provide useful information to the Physical Modeling Project (4.9). The original groundwater modeling project was scoped in 2007 to seek patterns in water-level (head) responses to increased recharge using a 3-D groundwater model, such as MODFLOW (Waldrick 2007). However, because little research has assessed the structural hydrogeological variability of deep-seated landslide catchments, a conceptual understanding of the range of recharge mechanisms ultimately affecting the propagation of pore pressure change in the shear zone is needed (Vallet et al., 2015). For example, a few of the known nonlinear subsurface heterogeneities that may affect the areal extent and timing of groundwater recharge within the recharge zone of landslide catchments include preferential flow paths, perched aquifers, and fissures (Bogaard and Greco, 2015). Besides geologic (stratigraphic) units and topography, the hydrologic characteristics of each landslide catchment will allow a more robust simulation of the spatial extent and temporal controls on groundwater recharge found in binned categories of deep-seated landslide types identified in the Landslide Classification Project.

This project would include the two phases of modeling proposed in the original 2007 scope, and would add a monitoring component to complement each modeling effort. A Phase 1 pilot project could include one of the hydrogeological and slope environments identified in the Deep-Seated Landslide Mapping Project (4.5) and assessed according to Landslide Classification Project (4.6) protocols. A subsequent phase would include modeling 2-4 additional settings.

The 2014 TFW Policy recommendations clarify that the "first step of the landslide classification project would be to bin glacial deep-seated landslides by landslide type, by stratigraphic section, by size of the landslide and *size of its groundwater recharge area*… as these attributes hypothetically have variable sensitivity to forest practices." In the 2007 scoping of this project, the areal extent of groundwater recharge affecting deep-seated landslides would be based on the combinations of geologic units and topography defined during the Landslide Classification

Project. However, Miller and Sias (1998) found, using linked hydrologic, groundwater, and slope stability models, that the recharge area inferred from surface observations can be incorrect, a problem inherent in applying models based on incomplete information (Miller, 2016). This concern is voiced by numerous other researchers, and could be avoided by assessing the potential complexity (or homogeneity) of structural features and time variable mechanisms that control differences in recharge areas feeding landslide catchment types.

The original project proposed to define the groundwater recharge area (GWRA) as the area of "significant" head change that would result from forest harvest, presumably due to ET reduction, but excluding other forest harvest influences, such as roads, fill, culverts, and yarding (that could inadvertently increase recharge to a landslide mass). All of the increase in water availability due to decreased ET would be assumed to reach the water table. However, this assumption is unlikely to apply to all landslide catchments, especially those with dynamic storage and drainage elements. A workable conceptual model of landslide catchment characteristics associated with particular stratigraphic and topographic settings would improve the reliability of modeled recharge rate time steps. Changes could then be simulated at daily, weekly, monthly, or any desired time step, for any length of time. Multi-year simulations of extended periods of wetter than average weather could also be modeled. Miller (2016) suggested that if modeling studies indicate both a groundwater response to forest practices and a landslide sensitivity to groundwater response, then soil-water balance models could be used to explore the range of recharge rates for the stand types and climates for landform classes identified in the Landslide Classification Project (4.6). The groundwater modeling could then be linked to slope stability modeling as a part of the physical modeling of deep-seated landslides, similar to the work of Brien and Reid (2008).

STRATEGY RECOMMENDATION

A pilot of the Groundwater Recharge Modeling Project will be conducted jointly with the pilot of Projects 4.5, 4.6 and 4.7 for a single deep-seated landslide that is representative of one of the initial classes identified in the pilot of the Landslide Classification Project (4.6). The pilot would aid in understanding potential differences in hydrogeological conditions needed to classify landslide types. It will also aid refinement of empirical study design of additional landslides. Following the bulk of the effort on the Landslide Classification Project, the Groundwater Recharge Modeling Project would be expanded to cover groundwater recharge assessment at other landslide sites. This project could also be linked to slope stability models and integrated into the Physical Modeling Project (4.10), if that project is pursued.

4.9 Physical modeling of Deep-seated Landslides (Initiation and Run-Out) – Pre-Scoping

Physical models can be used to integrate available information about individual landslides based on geologic and hydrologic processes. Fully integrated models, starting with tools developed during Projects 4.7 and 4.8, could be used to calculate the factor of safety of a landslide, the sensitivity to changes in pore pressure or toe erosion, a water budget and fluctuations in water supply for the landslide, the effect of forest cover on water supply, and the response in pore pressure caused by fluctuations in the water supply. In concert with the Landslide Classification Project (4.6), the distribution of calculated values can provide another way to characterize a population of landslides. Statistical methods can then be used to see how calculated values of stability, sensitivity, and precipitation correlate with the observed activity level.

Sensitivity of deep-seated landslides to forest practices is poorly understood. Data to characterize this sensitivity has not been systematically collected, and models to anticipate response of landslides to forest practices have been hindered by the need for detailed information on site stratigraphy and material properties. However, advances in techniques for assessing model sensitivity to poorly constrained parameters, availability of high-resolution LiDAR elevation data, and much more powerful computers offer new opportunities for identifying landslide hazards and assessing landslide sensitivity.

Strategy Recommendation

This project could involve two types of approaches to landslide modeling. The first involves developing techniques to link surface water, groundwater, and slope stability at specific locations and across broad areas. Few published examples of coupled models were identified in the literature reviews, and only one attempt to use models to assess timber harvest impacts on slope stability was found, but the potential to develop such as a model exists. Based on the results of the Landslide Classification Project (4.6) and the Groundwater Recharge Modeling Project (4.8), a selection of deep-seated landslide sites and broader settings could be identified for modeling.

A second approach involves developing generic representative landslide types and modeling the potential changes from harvest using linked hydrologic and slope stability models. The use of simplified, characteristic morphologies could help identify the dominant controls in different landslide settings.

4.10 Landslide Monitoring Project – Pre-Scoping

Miller (2016) recommended an approach using a combination of remote sensing (e.g., synthetic aperture radar) and field measurements to quantitatively measure activity of a population of landslides identified in the Landslide Classification Project (4.6) over time. Field data, such as precipitation, hydraulic head and landslide displacement could be collected to test assumptions about groundwater response and landslide activity in response to forest practices in different geomorphic settings. This recommendation was expanded in Miller (2017) to include dating of the landslide using surface roughness or direct ^{14}C dating of materials in the landslide.

Strategy Recommendation

Identify appropriate field sites, pose hypotheses about groundwater and landslide responses to future precipitation and forest practices, install arrays of piezometers, inclinometers, surface benchmarks, and precipitation gages, and collect data to test hypotheses and, if needed, modify conceptual frameworks. Success of field instrumentation and monitoring studies will depend greatly on site selection and study design. Results of statistical and modeling studies as described above can guide those efforts, providing information for identifying representative field sites and predictive models for posing hypotheses that rigorously test the basis of conceptual models.

4.11 Evapotranspiration Model Refinement Project- Scoped

This scoped project refines the evapotranspiration model (GAET), Project 4.1, which was developed by Sias (2003) using better quantified parameters, or the experimental pursuit of important parameters that have yet to be quantified (Sias 2007). This project was scoped to continue to inform the question: *Does harvesting the recharge area of a glacial deep-seated landslide promote its instability?* The model refinement project proposed to validate the GAET model using micrometeorological data from Vancouver Island, to establish model parameters and ranges for clearcut, intermediate and mature forests, and to field test the model. The field testing would yield information about model assumptions and direct researchers toward better quantification of important parameters. If field pilot testing is successful, then the model could be evaluated to determine if it is a cost-effective and robust tool for groundwater recharge modeling of forest practices.

Strategy Recommendation

At this time, our ability to interpret how additional water from loss of ET influences shallow groundwater levels and then slope stability is limited. Refinement of the actual value for loss of evapotranspiration is not currently helpful, but may be after other research is accomplished. Specifically, if we do not know what 40 inches of water per year means to a deep-seated landslide (typically value produced by the model for loss of evapotranspiration in high rainfall areas of Western Washington), then refining the value to 36 inches or 44 inches is not useful. If Groundwater Modeling (Project 4.8) and Physical Modeling (Project 4.9) improve our understanding of the influence of additional water on deep-seated landslides of different types, activity levels and geologic materials, then this project or improvement of a different model may become important in the future.

4.12 Empirical Evaluation of Deep-Seated Landslide Density, Frequency, and Runout by Landform

This project applies empirical methods to characterize susceptibility for deep-seated landslides and their run-out, and is described in the Draft Unstable Slopes Criteria Project - Research Alternatives (Unstable Slopes Criteria Technical Writing and Implementation Group, 17 January 2017 Draft). The project would include identifying suitable existing landslide inventories and collecting new inventories, which would expand the Deep-Seated Landslide Mapping Project (Project 4.5) to include bedrock landslides. The inventories would include run-out mapping of the slides, which would be used to calibrate empirical run-out models. Characteristics that differentiate active from inactive landslides would be identified and physical models would be used to synthesize these characteristics into useful metrics to estimate the potential for landslide activity. Based on the inventory, potentially unstable landforms would be identified and mapped.

The tasks described above are focused on determining landslide susceptibility. Sensitivity to forest practices will be examined in relation to natural factors by identifying differences in susceptibility with stand characteristics and the presence of forest roads.

Strategy Recommendation

This project scope will be captured in several other projects implemented as a part of the Strategy. Landslide density and frequency will be mapped as a part of Project 4.5. The association with different landforms will be included as a criterion for classification in Project 4.6. Run-out potential will be assessed by scenario modeling in Project 4.9.

5 Research Strategy Implementation

Implementation of the Strategy is expected to be a long-term process that refines our understanding of how forest practices affect the stability of deep-seated landslides through time. The initial phase of the strategy will likely involve several pilot projects linked together into a single scope of work. Since much of the strategy involves developing new methods, using pilot projects will help us better define the scope of the various projects. We envision the actual study designs will be structured across several projects:

Study Design 1: This study design includes Objective 1 of the Landslide Mapping Project (4.5) and a pilot Landslide Classification Project (4.6) to evaluate the sensitivity to forest practices using field reconnaissance and remote sensing. A preliminary GIS toolkit (Project 4.7) may be employed to identify relevant associations between attributes in the mapping and classification projects and landslide activity level. The third component includes pilot hydrologic field work and modeling (Project 4.8) to determine how much forest practices change the groundwater regimes for a single deep-seated landslide that represents a class of landslides that may be sensitive to forest practices;

Study Design 2: This study design includes Objectives 2 and 3 of the Landslide Mapping Project (4.5) and the main part of the Landslide Classification Project (4.6) to evaluate additional classes of landslides for their sensitivity to forest practices based on field and remotely sensed data. It also includes additional refinement of the GIS toolkit (Project 4.7) as the classifications are finalized;

Study Design 3: The third study design is for a greater effort of hydrogeologic modeling (Project 4.8) of representative landslides from the Landslide Classification Project and further refinement of the classifications (4.6);

Study Design 4: Using information from the hydrogeologic modeling and classification in the third study design, this study design covers physical modeling (Project 4.9) of representative landslides and further refinement of the classifications (4.6); and

Study Design 5: Long-term monitoring (Project 4.10) of representative landslide sites.

Together these linked modeling and empirical studies of representative classes of landslides will seek to determine whether forest practices have an impact on deep-seated landslide activity or reactivation potential. Information to help answer the Critical Questions will be provided at each step in the Strategy, although several of the broader questions will likely require information from multiple steps and may not be satisfactorily answered for more than a decade. Considerable uncertainties and inherent research limitations exist within the context and framework of the projects that define this Strategy. This is partly due to the challenges inherent in study design and model development, as well as the ability to collect data of sufficient resolution to characterize the complex relationships between deep-seated landslides and forest practices. As demonstrated by the previously completed literature syntheses, research has addressed components of the conceptual model linking forest practices to deep-seated landslide stability, but has yet to be integrated in a way that can address the Critical Questions.

Table shows the 10-year schedule and estimated annual budget for the projects outlined in the Strategy. The annual totals reflect the costs of staffing and contracting for the projects that would be occurring in that year, but not necessarily the costs of the individual study designs, which may extend over several years and be done concurrently with other studies. Additional details of the projects are provided in Table .

Table 2: Estimated ten-year budget projection for the deep-seated landslide strategy implementation (2018 dollars).

Project Description	**FY 2019**	**FY 2020**	**FY 2021**	**FY 2022**	**FY 2023**	**FY 2024-29 (annually)**
4.5 Mapping Objective 1	$75,000					
4.5 Mapping Objective 2		$100,000				
4.5 Mapping Objective 3			$100,000	$25,000	$25,000	$50,000
4.6 Pilot Classification	$50,000	$65,000				
4.6 Landslide Classification			$40,000	$25,000	$50,000	$50,000
4.7 Toolkit Development		$10,000	$10,000			
4.8 Pilot Groundwater Model		$25,000	$50,000			
4.8 Groundwater Modeling				$50,000	$50,000	$25,000
4.9 Physical Modeling				$75,000	$50,000	$25,000
4.10 Landslide Monitoring				$25,000	$25,000	$50,000
Total UPSAG Budget	*$125,000*	*$200,000*	*$200,000*	*$200,000*	*$200,000*	*$200,000*

** This is a long-term strategy and UPSAG recommends 1.0 FTE (~$125,000/yr) to maintain project continuity over time. Additional contract dollars ($50,000-$75,000/yr) to support the strategy will also be necessary to maintain progress on the projects defined under the strategy.*

Table 3: Deep-Seated Landslide Strategy Project List.

Project:	**4.1 Model Evapotranspiration in Deep-Seated Landslide Recharge Areas Project**	**4.2 Literature Synthesis of the Effects of Forest Practices on Glacial Deep-Seated Landslides and Groundwater Recharge Project**	**4.3 Literature Synthesis of the Effects of Forest Practices on Non-Glacial Deep-Seated Landslides and Groundwater Recharge Project**	**4.4 Board Manual Revision Project**	**4.5 Deep-Seated Landslide Map Project**	**4.6 Landslide Classification Project**	**4.7 GIS-Based Landslide Stability and Sensitivity Toolkit**	**4.8 Groundwater Recharge Modeling Project**	**4.9 Physical Modeling of Deep-Seated Landslides**	**4.10 Landslide Monitoring Project**	**4.11 Evapotranspiration Model Refinement Project**	**4.12 Empirical Evaluation of Deep-Seated Landslide Density, Frequency, and Runout by Landform**
Project Origin	CMER Work Plan	CMER Work Plan	Deep-Seated Landslide Proposal Initiation (PI)	CMER Work Plan	CMER Work Plan	CMER Work Plan / Revised by PI	Glacial deep-seated literature review (Miller 2016)	CMER Work Plan	Non-glacial deep-seated literature review (Miller 2017)	Glacial deep-seated literature review (Miller 2016)	CMER Work Plan	Unstable Slopes Criteria TWIG
Status	Completed	Completed	Completed	On-going	On-hold	Scoped, on-hold	Pre-scoping	Scoped, on-hold	Pre-scoping	Pre-scoping	Scoped, on-hold	Pre-scoping
Sequence	N/A	N/A	N/A	Periodically Updated	Step 1: Objective 1 for landslide sample to initiate pilots for 4.6, 4.7 and 4.8; coordinated with WGS. Objective 2 mapping will continue concurrent with 4.6. Step 5: Objective 3 mapping will continue until completion	Step 2a: Requires data from 4.5.	Step 2b: Tools for geomorphic characterization developed co-operatively with 4.5 and 4.6.	Step 2c: pilot following pilot for 4.6; Needed for 4.9. Step 3a: expansion of modeling to other representative landslides.	Step 3b: Informed by 4.6; Requires data from 4.8.	Step 4: Location(s) for long-term data collection predicated on 4.5-4.9.	If needed to inform 4.8.	Incorporated into previous steps, especially 4.6.
Priority	N/A	N/A	N/A	When appropriate	Necessary for beginning pilot projects of 4.6, 4.7 and 4.8; Additional mapping in Objective 3 may provide an important Rule Tool.	Necessary	Would be useful	Necessary	Necessary	Necessary	Low (at the present time)	N/A

Project:	4.1 Model Evapotranspiration in Deep-Seated Landslide Recharge Areas Project	4.2 Literature Synthesis of the Effects of Forest Practices on Glacial Deep-Seated Landslides and Groundwater Recharge Project	4.3 Literature Synthesis of the Effects of Forest Practices on Non-Glacial Deep-Seated Landslides and Groundwater Recharge Project	4.4 Board Manual Revision Project	4.5 Deep-Seated Landslide Map Project	4.6 Landslide Classification Project	4.7 GIS-Based Landslide Stability and Sensitivity Toolkit	4.8 Groundwater Recharge Modeling Project	4.9 Physical Modeling of Deep-Seated Landslides	4.10 Landslide Monitoring Project	4.11 Evapotranspiration Model Refinement Project	4.12 Empirical Evaluation of Deep-Seated Landslide Density, Frequency, and Runout by Landform
Project Outcomes	Model to calculate loss of ET by timber harvest utilizing Sias (2003).	Best available science for deep-seated landslides in glacial materials.	Best available science for deep-seated landslides in bedrock materials.	Updated Board Manual 16 as new information is developed.	GIS database of SLIP-mapped deep-seated landslides including additional key attributes that are relevant to forest practices and known geotechnical investigations of the site.	From 4.5, augment database for selected DSL with field and remotely sensed attributes including verified or revised stratigraphy and activity levels. Bin into potentially meaningful categories. By category, do detailed analyses using both field evidence and aerial photo assessment to correlate movement to potential environmental or land use influences.	The toolkit would provide simple GIS-based tools to assess attributes of landslides that are likely related to slope stability, including tools to help identify and classify the groundwater recharge area. Frequency distributions of landslide attributes, and statistical analyses to stratify landslides by differences in those distributions. These tools would be used to fill data attributes in the landslide database and as components of future geotechnical landslide hazard assessments for forest-practice applications	Pilot will develop a conceptual model for hydrologic processes in deep-seated landslides by looking at one hillslope and geologic setting identified in the Landslide Classification Project and begin modeling of recharge, storage and drainage of a representative landslide. Phase 2 would include modeling 2-4 additional settings. Groundwater pathways based on landslide type. Effective, reproducible groundwater models applicable to the various DSL types.	Calibrated physical models or techniques to link surface water, groundwater, and associated slope stability processes. The project would include scenario modeling of potential changes in geometry, climate or land-use.	The monitoring project will use a combination of remote sensing and field measurements to quantitatively measure changes in landslide activity for a population of landslides as a result of changes in hydrology or slope geometry. This project would provide validation monitoring of the conceptual groundwater and slope stability models developed in 4.8 and 4.9.	At the present time, our ability to interpret how additional water from loss of ET influences shallow groundwater levels and then slope stability is limited. More precise values for the loss of ET are not currently helpful, but may be after other research is accomplished.	N/A

Project:	4.1 Model Evapotranspiration in Deep-Seated Landslide Recharge Areas Project	4.2 Literature Synthesis of the Effects of Forest Practices on Glacial Deep-Seated Landslides and Groundwater Recharge Project	4.3 Literature Synthesis of the Effects of Forest Practices on Non-Glacial Deep-Seated Landslides and Groundwater Recharge Project	4.4 Board Manual Revision Project	4.5 Deep-Seated Landslide Map Project	4.6 Landslide Classification Project	4.7 GIS-Based Landslide Stability and Sensitivity Toolkit	4.8 Groundwater Recharge Modeling Project	4.9 Physical Modeling of Deep-Seated Landslides	4.10 Landslide Monitoring Project	4.11 Evapotranspiration Model Refinement Project	4.12 Empirical Evaluation of Deep-Seated Landslide Density, Frequency, and Runout by Landform
Estimated Cost	N/A	N/A	N/A	N/A - WADNR responsibility outside of CMER.	See Table 2. 0.5 FTE for all years for Objectives 1 and 2; full FTE for subsequent years until Objective 3 is completed. SLIP mapping will be completed by WGS over the next several years. Additional information will be needed and additional spatial coverage may be needed for our purposes.	See Table 2. 0.5 FTE for all years (with 4.5). CMER staff geomorphologist or TWIG member for GIS support and some field effort to provide a linkage to 4.7 (.1 FTE).	See Table 2. CMER staff geomorphologist or TWIG member (.1 FTE).	See Table 2. Pilot development: 0.25 FTE for first year, potentially increasing to 0.5 FTE for second year, or equivalent contract.	See Table 2. 2-year consulting contract.	See Table 2. The project will require the acquisition of monitoring equipment and ~0.5 FTE for multiple years.	See Table 2. $55,000 (2007 estimate)	N/A
Approximate Time	N/A	N/A	N/A	N/A	Developing a sample of SLIP-mapped landslides could be accomplished within 3 months. Developing a definitive landslide inventory that expands the SLIP attributes would likely take 10 years, unless additional resources are provided for LiDAR and expanded mapping.	Pilot would take 4 months simultaneous with 4.5 and 4.7. Complete project would take 2 years.	Development of the toolkit would likely take 2 years simultaneous with the pilot and larger landslide classification project (4.6).	Pilot would take 1 year. Modeling of Phase 2 (2-4 additional landslides) would require 2 additional years.	2 years for model development at several representative landslide locations.	Long-term monitoring (10 years)	6 months (based on 2007 scoping)	N/A

Project:	4.1 Model Evapotranspiration in Deep-Seated Landslide Recharge Areas Project	4.2 Literature Synthesis of the Effects of Forest Practices on Glacial Deep-Seated Landslides and Groundwater Recharge Project	4.3 Literature Synthesis of the Effects of Forest Practices on Non-Glacial Deep-Seated Landslides and Groundwater Recharge Project	4.4 Board Manual Revision Project	4.5 Deep-Seated Landslide Map Project	4.6 Landslide Classification Project	4.7 GIS-Based Landslide Stability and Sensitivity Toolkit	4.8 Groundwater Recharge Modeling Project	4.9 Physical Modeling of Deep-Seated Landslides	4.10 Landslide Monitoring Project	4.11 Evapotranspiration Model Refinement Project	4.12 Empirical Evaluation of Deep-Seated Landslide Density, Frequency, and Runout by Landform
Required Skills	N/A	N/A	N/A	N/A	Experience assessing landslide type, stability, and geologic materials in the field. Experience using GIS to map deep-seated landslides from LiDAR-derived elevation models.	In addition to two qualifications listed for 4.5, experience mapping DSL from basic DEM and aerial photography. Experience interpreting subsurface data sources, such as well logs and geophysical surveys.	Experience with GIS model building, including familiarity with basic 2-dimensional slope stability models.	Experience with three-dimensional groundwater modeling in deep-seated landslide deposits.	Experience with site assessment of deep-seated landslides, *potentially including subsurface exploration and landslide instrumentation for model calibration.* Experience with using and coupling hydrologic, groundwater and slope stability models.	Experience placing hydrologic and motion-sensing equipment, maintaining same, and interpreting/analyzing the data.	Experience with ET models and research. Research might be done in cooperation with a university (e.g., UBC).	N/A

Project:	4.1 Model Evapotranspiration in Deep-Seated Landslide Recharge Areas Project	4.2 Literature Synthesis of the Effects of Forest Practices on Glacial Deep-Seated Landslides and Groundwater Recharge Project	4.3 Literature Synthesis of the Effects of Forest Practices on Non-Glacial Deep-Seated Landslides and Groundwater Recharge Project	4.4 Board Manual Revision Project	4.5 Deep-Seated Landslide Map Project	4.6 Landslide Classification Project	4.7 GIS-Based Landslide Stability and Sensitivity Toolkit	4.8 Groundwater Recharge Modeling Project	4.9 Physical Modeling of Deep-Seated Landslides	4.10 Landslide Monitoring Project	4.11 Evapotranspiration Model Refinement Project	4.12 Empirical Evaluation of Deep-Seated Landslide Density, Frequency, and Runout by Landform
Critical Questions	Work plan: Does harvesting of the groundwater recharge area of a glacial deep-seated landslide promote its instability?	Work plan: Does harvesting of the groundwater recharge area of a glacial deep-seated landslide promote its instability?	PI Questions: Are GWRAs associated with bedrock DSLs? How do GWRAs affect bedrock DSL? How do forest practices affect these GWRAs? What are the best methods to assess reactivation potential from dormant DSLs of any type? What are the characteristics of large landslides that may predispose them to long, rapid run-out or composite failure? What methods might improve prediction? What are the best tools to assess run-out potential for DSL?	N/A (answers to critical questions will improve the Board Manual)	Work plan: Can relative levels of response to forest practices be predicted by key characteristics of glacial deep-seated landslides and/or their groundwater recharge areas? PI Questions: How do GWRAs affect bedrock DSL? How do forest practices affect these GWRAs?	Work plan: Can relative levels of response to forest practices be predicted by key characteristics of glacial deep-seated landslides and/or their groundwater recharge areas? PI Questions: How do GWRAs affect bedrock DSL? How do forest practices affect these GWRAs? What are the characteristics of large landslides that may predispose them to long, rapid run-out or composite failure?	Work plan: Can relative levels of response to forest practices be predicted by key characteristics of glacial deep-seated landslides and/or their groundwater recharge areas? PI Questions: How do GWRAs affect bedrock DSL? How do forest practices affect these GWRAs? What are the best methods to assess reactivation potential from dormant DSLs of any type? What are the characteristics of large landslides that may predispose them to long, rapid run-out or composite failure? What methods might improve prediction? What are the best tools to assess run-out potential for DSL?	Work plan: Does harvesting of the groundwater recharge area of a glacial deep-seated landslide promote its instability? PI Question: How do forest practices affect these [bedrock] GWRAs?	Work plan: Can relative levels of response to forest practices be predicted by key characteristics of glacial deep-seated landslides and/or their groundwater recharge areas? PI Questions: How do forest practices affect these [bedrock] GWRAs? What are the best methods to assess reactivation potential from dormant DSLs of any type? What are the characteristics of large landslides that may predispose them to long, rapid run-out or composite failure? What methods might improve prediction? What are the best tools to assess run-out potential for DSL?	Work plan: Does harvesting of the groundwater recharge area of a glacial deep-seated landslide promote its instability? Can relative levels of response to forest practices be predicted by key characteristics of glacial deep-seated landslides and/or their groundwater recharge areas? PI Questions: How do GWRAs affect bedrock DSL? How do forest practices affect these GWRAs?	Work plan: Does harvesting of the groundwater recharge area of a glacial deep-seated landslide promote its instability? PI Question: How do forest practices affect these [bedrock] GWRAs?	N/A

Project:	4.1 Model Evapotranspiration in Deep-Seated Landslide Recharge Areas Project	4.2 Literature Synthesis of the Effects of Forest Practices on Glacial Deep-Seated Landslides and Groundwater Recharge Project	4.3 Literature Synthesis of the Effects of Forest Practices on Non-Glacial Deep-Seated Landslides and Groundwater Recharge Project	4.4 Board Manual Revision Project	4.5 Deep-Seated Landslide Map Project	4.6 Landslide Classification Project	4.7 GIS-Based Landslide Stability and Sensitivity Toolkit	4.8 Groundwater Recharge Modeling Project	4.9 Physical Modeling of Deep-Seated Landslides	4.10 Landslide Monitoring Project	4.11 Evapotranspiration Model Refinement Project	4.12 Empirical Evaluation of Deep-Seated Landslide Density, Frequency, and Runout by Landform
Specific Research Questions					What is the distribution of deep-seated landslides across forest lands in Washington State? What are the key attributes, such as activity level, geologic materials, or landslide type associated with these features? Are landslide attributes and activity levels correlated to land use?	What statistical groupings exist within the population of deep-seated landslides? Can landslides be grouped into classes that exhibit different responses to forest practices?	Can a basic set of GIS-tools be developed to assess landslide stability and sensitivity to forest practices from currently available spatial data?	What are the patterns and the controlling processes that drive the dominant hydrologic responses to increased recharge? From Waldrick (2007): What are the empirically derived areas beyond which recharge changes are not likely to affect a deep-seated landslide? How is the recharge area defined with respect to both topography and hydrogeology?	Can physical models be used with available data to predict landslide response to forest practices?	Is there a difference in pre- and post-harvest groundwater response to precipitation? Is there a difference in pre- and post-harvest landslide rate of movement?		N/A

Project:	4.1 Model Evapotranspiration in Deep-Seated Landslide Recharge Areas Project	4.2 Literature Synthesis of the Effects of Forest Practices on Glacial Deep-Seated Landslides and Groundwater Recharge Project	4.3 Literature Synthesis of the Effects of Forest Practices on Non-Glacial Deep-Seated Landslides and Groundwater Recharge Project	4.4 Board Manual Revision Project	4.5 Deep-Seated Landslide Map Project	4.6 Landslide Classification Project	4.7 GIS-Based Landslide Stability and Sensitivity Toolkit	4.8 Groundwater Recharge Modeling Project	4.9 Physical Modeling of Deep-Seated Landslides	4.10 Landslide Monitoring Project	4.11 Evapotranspiration Model Refinement Project	4.12 Empirical Evaluation of Deep-Seated Landslide Density, Frequency, and Runout by Landform
Advantages of Approach	One goal of the project was to develop a model that could be used as a tool to assess decreases in ET in response to timber harvest in the context of deep-seated landslide response. A simple modeling tool would allow land managers to quickly assess potential sensitivity to forest practices.	The literature review and database provides an updated Best Available Science that will be used for further research project development.	The bedrock deep-seated literature review and database supplements the glacial deep-seated literature review to provide the basis for further project development.	Periodically updating the Board Manual will ensure that practitioners are using the best available science for identifying and assessing deep-seated landslides.	The approach builds on work that is already underway by the WGS. Our efforts provide needed mapping and data to carry forward with 4.6-4.10. Ultimately, a complete inventory of glacial valley-fill landslides will help land managers and reviewers recognize deep-seated landslide hazards.	The approach categorizes DSL such that future modeling and empirical efforts would be focused on representative norms, increasing the inference by leading to hazards and sensitivities being assigned for category while limiting the costs of the total effort.	The tools could provide consistent, replicable methods for landslide characterization. The approach would allow rapid and cost-effective assessment of deep-seated landslide sensitivity. Would create GIS tools to evaluate LiDAR data as they are acquired for additional areas of Washington.	Project will provide subsurface data to characterize the stratigraphy and hydraulic properties of the groundwater recharge area and subsurface flow paths. Modeling can lead to a better understanding of GWRA delineation and improve our knowledge about deep-seated landslide sensitivity to land use. Groundwater models, such a MODFLOW, have been linked to slope stability models (Brien and Reid 2008) to provide the basis for the physical modeling proposed in Project 4.9.	Linking hydrologic and slope stability models will allow for Factor-of-Safety assessment of existing characteristic deep-seated landslides selected from the bins identified in 4.6. Scenario modeling of changes in climate, geometry and land use will be used to assess the sensitivity and reactivation potential of these landslides, increasing the inference of the project and providing more sophisticated tools to QEs.	Using empirical methods to assess changes in landslide activity from different forest practices will provide validation of the modeling that was conducted in 4.10.	Improved modeling of evapotranspiration would be valuable for assessing groundwater recharge to deep-seated landslides. The GAET model has been developed specifically to assess the impacts of timber harvest under local climate conditions.	N/A
Disadvantages, limitations, and inherent uncertainties	Modeling left several areas of uncertainty largely related to model selection and parameterization. Addressing these would require developing 4.11.	Limited sources were found that directly addressed forest practices effects on glacial deep-seated landslides.	Limited sources were found that directly addressed forest practices effects on non-glacial deep-seated landslides.	N/A	WGS will likely need additional resources to complete the mapping envisioned in the definitive landslide inventory. LiDAR is not available for portions of the regulated forest environment and will need to be acquired before mapping can be done. Additional attributes suggested by Miller (2016) in the landslide inventory will require substantial field work.	Does not result in a total DSL inventory for all of Washington State.	Due to the complexity of deep-seated failures, generalized slope stability modeling based on GIS analysis could lead to misinterpretation of individual sites.	Modeling will require testing of new methods to describe internal landslide dynamics.	Modeling will require developing the means of coupling existing models to reflect the connection between groundwater recharge and slope stability. Model validation may require substantial data collection.	A small sample size may limit more broad inferences about other deep-seated landslides.	Refining ET estimates, in the absence of coupled models to connect changes in shallow groundwater to slope stability, does not advance our understanding of deep-seated landslide sensitivity to forest practices. Once coupled hydrologic and slope stability models are developed (4.8 and 4.9), then refining ET estimates could become important.	N/A

6 REFERENCES

Bogaard, T. A. and Greco, R. 2015. Landslide hydrology: from hydrology to pore pressure. WIREs Water, 3: 439–459. doi:10.1002/wat2.1126

Brien, D. L. and Reid, M. E. 2008. Assessing deep-seated landslide susceptibility using 3-D groundwater and slope-stability analyses, southwestern Seattle, Washington, in Baum, R.L., Godt, J.W. and Highland, L.M., eds. Landslides and Engineering Geology of the Seattle, Washington, Area: Geological Society of America Reviews in Engineering Geology V. XX, p. 83-101.

Cooperative Monitoring, Evaluation and Research Committee. 2017. 2017-2019 Biennium CMER Work Plan. March 2017. 157 pp.

Gerstel, W. 2007. CMER Scoping Template for the Geo/Hydro/Geomorphic Landslide Classification Project.

King County. 2016. Mapping of Potential Landslide Hazards along the River Corridors of King County, Washington. Prepared by River and Floodplain Management Section, Water and Land Resources Division, Department of Natural Resources and Parks. Seattle, WA. August.

Mickelson, K. A., Jacobacci, K. E., Contreras, T. A, Biel, Alyssa and Slaughter, S. L. 2017, Landslide inventory, susceptibility, and exposure analysis of Pierce County, Washington: Washington Geological Survey Report of Investigation 39, 16 p. text, with 2 accompanying ESRI file geodatabases and 1 Microsoft Excel file.

Miller, D. 2016. Literature synthesis of the effects of forest practices on glacial deep-seated landslides and groundwater recharge. Prepared for the Upslope Processes Scientific Advisory Group, Cooperative Monitoring, Evaluation and Research Committee.

Miller, D. 2017. Literature synthesis of the effects of forest practices on non-glacial deep-sated landslides and groundwater recharge. Prepared for the Upslope Processes Scientific Advisory Group, Cooperative Monitoring, Evaluation and Research Committee.

Miller, D.J. and Sias, J. 1998. Deciphering large landslides: linking hydrological, groundwater and slope stability models through GIS. Hydrological Processes 12, 923-941 (1998).

Sias, J. 2003. Estimation of multi-season evapotranspiration in relation to vegetation cover for regions with rainy-winter/ dry-summer climate. Prepared for the Upslope Processes Scientific Advisory Group, Cooperative Monitoring, Evaluation and Research Committee.

Sias, J. 2007. CMER Scoping Template for the Refinement of the Sias model using better quantified parameters. WADNR PSC-07-115, June 27, 2007.

Slaughter, S. L.; Burns, W. J.; Mickelson, K. A.; Jacobacci, K. E.; Biel, Alyssa; Contreras, T. A. 2017. Protocol for landslide inventory mapping from LiDAR data in Washington State: Washington Geological Survey Bulletin 82, 27 p. text, with 2 accompanying ESRI file geodatabases and 1 Microsoft Excel file.

Timber/Fish/Wildlife Policy Committee. 2016. Unstable slopes proposal initiation; recommendations from TFW Policy Committee to Forest Practices Board. August 4, 2016.

Vallet, A., Bertrand, C., Mudry, J., Bogaard, T., Fabbri, O., Baudement, C., Régent, B. 2015. Contribution of time-related environmental tracing combined with tracer tests for characterization of a groundwater conceptual model: a case study at Séchilienne landslide, western Alps (France). Hydrogeology Journal: DOI 10.1007/s10040-015-1298-2.

Waldrick, L. 2007. CMER Scoping Template for the Groundwater Recharge Areas Modeling Project.

Washington Forest Practices Board, November 2015. Section 16 Unstable Slopes. Forest Practices Board Manual.

Appendix A: CMER Work Plan Summaries

4.1 Model Evapotranspiration in Deep-seated Landslide Recharge Area Project (Modified from 2016 CMER Work Plan)

This completed project developed an analytical model for assessing the evapotranspiration changes resulting from timber harvest. The model was intended to be applied to timber harvest within the recharge area of deep-seated landslides in glacial sediments. However, the model has not been directly validated and refined because of insufficient field data to verify model parameters. As such, UPSAG and CMER did not recommend a policy change, even though the results of the model suggest that there is likely a significant, detectable change in water availability when converting an entire groundwater recharge area from mature forest to a clear-cut. A follow-up validation/refinement study could be pursued as a second phase, as described below.

4.2 Literature Synthesis of the Effects of Forest Practices on Glacial Deep-Seated Landslides and Groundwater Recharge (From 2016 CMER Work Plan)

This project is a focused literature review to summarize the best available science on the effects of forest practices on deep-seated landslides in glacial materials. UPSAG undertook the first phase of the project, Literature Synthesis of the Effects of Forest Practices on Glacial Deep-Seated Landslides and Groundwater Recharge, in 2015 to provide updated background information to help address the question: "Does harvesting of the groundwater recharge area of a glacial deep-seated landslide promote its instability?" The synthesis found that the sensitivity of glacial deep-seated landslides to forest practices is poorly understood and that many of the effects of forest practices must be inferred using measurements for different land-cover types (Miller 2016).

4.3 Literature Synthesis of the Effects of Forest Practices on Non-Glacial Deep-Seated Landslides and Groundwater Recharge (Modified from 2016 CMER Work Plan)

This project is a companion project to the literature synthesis focused on deep-seated landslides in glacial materials, but focuses on non-glacial materials. UPSAG undertook the project in October 2016 to address questions related to the effects of harvesting of the groundwater recharge area of non-glacial deep-seated landslides on slope stability. An Unstable Slopes Proposal Initiation (PI), generated by the Board led to a memo "Recommendations from TFW Policy Committee to Forest Practices Board", dated August 4, 2016, which helped inform the questions posed for the literature synthesis.

4.4 Board Manual Revision Project (Modified from 2016 CMER Work Plan)

This potential project would involve revisions of the Board Manual (Section 16) to more clearly describe which deep-seated landslides are at risk and what intensity of study might be needed based on the activity level of the landslide described by the groundwater recharge rule. In 2014, WADNR convened an "Expert Panel" to revise portions of the Board Manual. A section on landslide run out and potential delivery was later revised by a TFW stakeholder group of qualified experts. The Board adopted the revised version of Section 16 in March 2015, and the section on run out and delivery in November 2015, but additional revisions are ongoing. The 2014–2015 revisions to Section 16 provided new guidance regarding the amount of study needed to address different situations. A review of existing geotechnical reports might provide additional ideas about analysis and interpretation of field evidence. Ultimately, the Landslide Classification Project will provide information about hazards and sensitivities.

4.5 Deep-Seated Landslide Map Project (Proposed)

This project would build on published SLIP mapping completed by the WGS to develop a comprehensive landslide inventory for forestlands. Additional attributes that are relevant to forest practices would be appended to the SLIP mapping and information from any relevant geotechnical investigations included. This project is a simple rule tool that will be useful to land managers, stakeholders and regulators; a selection of mapped landslides would also be needed for the scoping of the Landslide Classification Project.

4.6 Landslide Classification Project (Modified from 2016 CMER Work Plan)

This potential project, as scoped in 2007, would categorize the common stratigraphic and geomorphic situations present among deep-seated landslides in glacial sediments to hypothetically evaluate which situations are most sensitive to changes in groundwater produced by upslope timber harvest. The 2014 Policy recommendations clarify that the first step would bin glacial deep-seated landslides by landslide type, by stratigraphic section, by size of the landslide and size of its groundwater recharge area, and by proximity to a river channel as these attributes hypothetically have variable sensitivity to forest practices. Policy recommended a second step, as long envisioned by UPSAG, that the range of potential sensitivities be empirically analyzed to test the degree to which forest practices have influence on one or more of the bins.

4.7 GIS-based Landslide Stability and Sensitivity Toolkit (Proposed)

The proposed project will provide land managers and reviewers a GIS-based toolkit to assess deep-seated landslide stability and sensitivity.

4.8 Groundwater Recharge Modeling Project (2016 CMER Work Plan)

This project would use groundwater recharge monitoring and modeling to evaluate which parts of the groundwater recharge zone are most influential on landslide movement. This project would add critical hydrologic components to the stratigraphic and geomorphic characteristics that define common landslide types that are likely to be most sensitive to increased recharge.

4.9 Physical modeling of Deep-seated Landslides (Proposed)

This project involves using coupled hydrologic and slope stability models to characterize existing deep-seated landslides, or simplified landslide settings.

4.10 Landslide Monitoring Project (Proposed)

This potential project involves instrumenting a population of deep-seated landslides and quantitatively measuring changes in activity level in response to changes in hydrology or slope geometry. It is anticipated that different scenarios, including different harvest techniques, would be evaluated. This project will be a useful companion to the Physical Modeling project to help validate the modeling.

4.11 Evapotranspiration Model Refinement Project (2016 CMER Work Plan)

This potential project would use fine-scale meteorological data to validate or refine the existing evapotranspiration model, and would develop materials to facilitate application of the model. UPSAG presently recommends that this project not be pursued due to the low likelihood that fundamental scientific uncertainties will be resolved.

4.12 Empirical Evaluation of Deep-Seated Landslide Density, Frequency, and Runout by Landform (TWIG Project)

(This project is not proposed for inclusion in the CMER Work Plan.)